PREPRINT UCRL- 81696

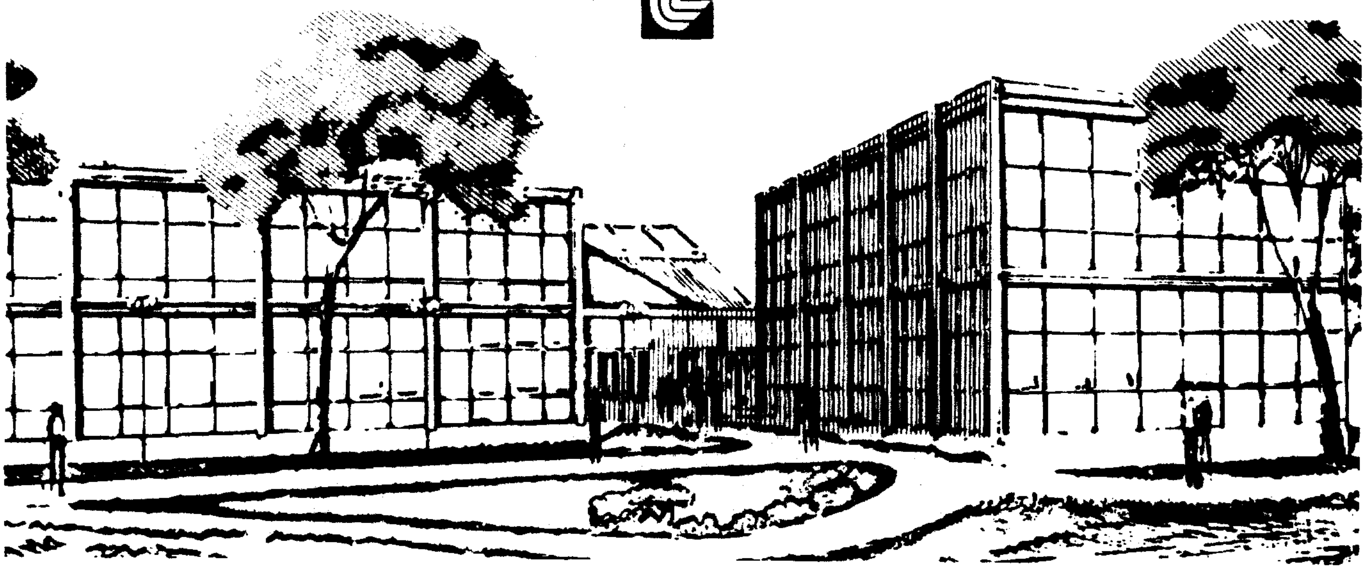
Lawrence Livermore Laboratory

SITE SOIL COLUMN CONSIDERATIONS IN SEISMIC HAZARD ANALYSIS

Don L. Bernreuter

December 1978

This paper was prepared for the Third ASCE Specialty Conference on Structural Design of Nuclear Power Plants, Boston, Massachusetts, April, 3-5, 1979.



SITE SOIL EFFECTS IN SEISMIC HAZARD ANALYSIS

Don L. Bernreuter

KEY WORDS: Acceleration; Attenuation; Earthquake Magnitude; Earthquakes; Ground Motion; Hazard Analysis; Soil Column; Spectral Amplification; Statistical Analysis; Travel Path

ABSTRACT

A theoretical approach is used to show the importance of differences in earthquake-generating mechanisms. Data from underground nuclear explosions are used to show the importance of slight variations in travel path. The influence of the site is studied using two approaches. The first approach is to use data recorded at the same site during a number of different earthquakes. The second approach is to fix the earthquake, in this case the San Fernando earthquake, and examine all sites that are "one-sigma sites" to see if there is a common generic site type that significantly amplifies the ground motion.

It is concluded that generally fixing the site does not reduce the variation of the data. At site-resonant frequencies, the spectral response is greater than envelope spectra of Regulatory Guide 1.60. Small near-field earthquakes have significantly greater high-frequency content than is contained in Regulatory Guide 1.60. Finally, no generic site condition could be determined that consistently amplified the ground motion from the San Fernando earthquake.

SITE SOIL EFFECTS IN SEISMIC HAZARD ANALYSIS*

Don L. Bernreuter†

INTRODUCTION

Probabilistic approaches for defining the level of ground motion to be used for the structural design of nuclear power plants are relatively new and are not currently used in the licensing of nuclear power plants. There is, however, considerable movement toward using probabilistic methods to judge the overall safety of the deterministic approach now in use. An illustration of this movement is the Pacific Gas and Electric Company's (PG&E) Amendment 52 for the Diablo Canyon Reactor (1). Furthermore, Smith et al. (2) outline a major program funded by the NRC that uses a probabilistic approach to assess the current seismic analysis methodology.

One of the main difficulties with both the deterministic and probabilistic approaches is that of properly accounting for local site soil column effects. A simple method is generally used to account for the local soil column in probabilistic approaches. Typically, local site effects are accounted for by use of a simple soil classification procedure such as that introduced by Trifunac and Brady (3). In this simple approach, the site's influence on ground motion is handled by using correlations for the soil classification appropriate for the site.

---

*This work was supported by the U.S. Nuclear Regulatory Commission, Office of Seismic Research, under Interagency Agreement DOE 40-550-75 with the U.S. Department of Energy.

†Current employment: Lawrence Livermore Laboratory, University of California, Livermore, California 94550

However, the use of such a simple approach could lead to the introduction of large systematic errors in the analysis. Two major errors can occur: (1) Projected ground motion estimates for a site are based on correlations developed from data obtained at a number of loosely correlated sites; hence, there is little correlation between the spectral peaks from site to site. Thus, the spectral peaks at one site are averaged with spectral lows for another site. However, the ground motion at a given site may consistently amplify the incoming seismic energy at certain frequency intervals. The net result is that the projected ground motion estimates may be biased on the low side for such a site. (2) The statistic (typically the standard deviation) that measures the dispersion or spread of the data about the mean could be smaller than that for data recorded at different loosely correlated sites.

The importance of and need to understand the first possible error is of considerable interest in assessing the current approach used to license nuclear power plants. In the current approach (outlined in detail in Ref. 4), the same smoothed spectrum based on the mean and standard deviation of the spectral amplification factors from data obtained at a number of different sites is used as input free-field surface motion for all sites.

The value of standard deviation is also of interest because it has a significant effect on the seismic hazard projected for a site.

This paper investigates these phenomena. The ideal way to address this question is to keep the site fixed and see how the spectra change as a function of changing the source, the travel path, or the level of ground shaking. In general, it is not possible to do this. First, the variations introduced by source and travel path are briefly examined. Then the influence of the site is studied. Two different approaches are taken to study the influence of the site. One approach is to use data recorded at the same site but resulting from a number of different earthquakes; such data are grouped to minimize the variation introduced by source travel path and level of ground shaking effects. The other approach used is to fix the earthquake (San Fernando) and examine the sites that are "one-sigma sites," i.e., sites whose response is significantly above or below the majority of sites at any given epicentral distance to see if a common generic site type significantly amplifies the ground motion.

VARIATIONS DUE TO SOURCE EFFECTS

This section examines how variations in the earthquake-generating mechanism influence the spectral shape and level of the ground motion. It is generally assumed that earthquakes are basically similar and that the variation due to earthquake "strength" can be accounted for by including magnitude in the correlation.

Bernreuter (5) and Trifunac (6) show that, disregarding site effects, the high-frequency part of the spectrum is controlled by the dynamic stress drop of the earthquake, which is the stress difference between the dynamic stress concentration at the rupture front and the dynamic friction on the fault behind the rupture, and the corner frequency is controlled by a parameter related to the area of the highly stressed zone of the fault. These effects are illustrated in Fig. 1. The various measures of the magnitude of an earthquake are empirical quantities and cannot be directly related to the various source models. However, empirical relations have been obtained (5,7):

$$M_L = 3/2 \log L + \log \Delta\sigma + C \quad , \qquad (1)$$

where

M_L = Local Richter magnitude

L = Appropriate fault dimension

$\Delta\sigma$ = Stress drop.

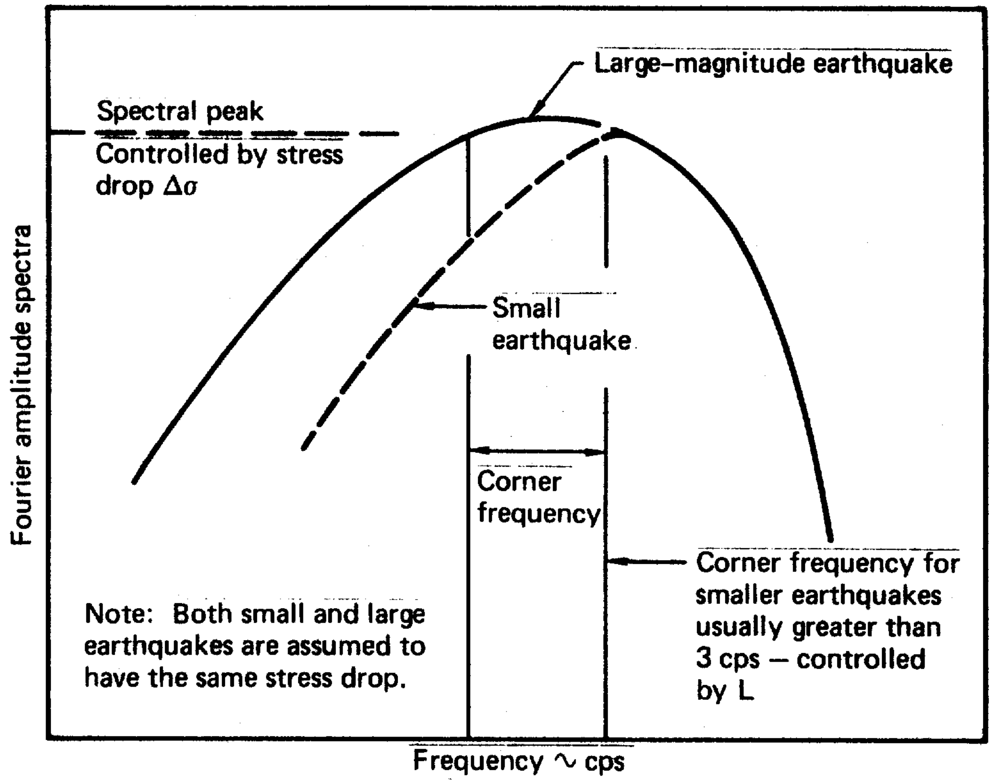


FIG. 1. Effects of change in earthquake magnitude on spectral shape and level

At least two orders of magnitude variation in the stress drop have been observed (5,7). Thus, significantly different spectral shapes and/or peak ground motion values can be expected from earthquakes with the same magnitude but with different L's and $\Delta\sigma$'s. This variation is illustrated in Fig. 2 taken from Ref. 5 for two earthquakes of $M_L = 5.6$ and a factor of 10 difference in stress drop.

Unfortunately, determining the basic source parameters of a given earthquake is difficult. The interpretation is made more difficult because the simple model (5) used to calculate the parameters L and $\Delta\sigma$ is restricted to direct body waves. Thus, the simple model does not include surface waves and complexly reflected body waves, which can have a significant influence on the spectral shape.

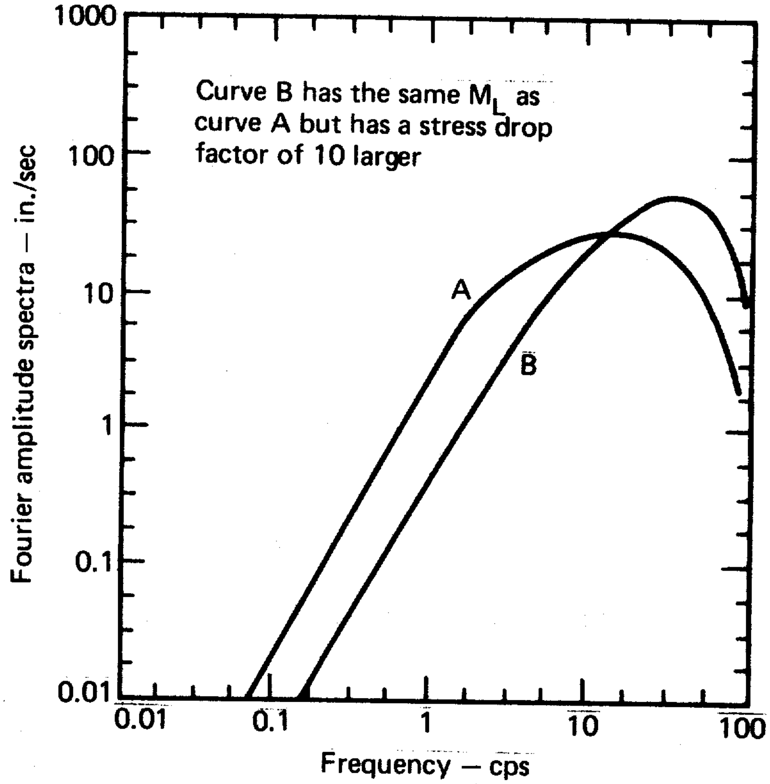


FIG. 2. Effect of increased stress drop for same magnitude earthquake on fourier amplitude spectra.

It is seen from Fig. 2 that significant uncertainty--reflected by large values of standard deviation--must be expected in various correlations defining the possible ground motion from earthquakes if only magnitude is used as the sole source parameter (5).

VARIATIONS DUE TO TRAVEL PATH

Ideally, to study travel path effects, one would like to keep the site and earthquake-generating mechanism fixed and allow only the source location to vary. This is difficult to achieve. One source of useful data does exist--namely, the observed ground motion from large underground nuclear explosions (UNE). Bernreuter et al. (8,9) showed that the spectral content of such ground motion is very similar to earthquake ground motion.

Figure 3 shows the comparison of the spectra observed at the motel in Tonopah, Nevada, from the HANDLEY and BOXCAR UNEs. Both of these explosions are of similar yield and were located about 4 km apart in the Pahute Mesa of the Nevada Test Site. The distance to the site is about 105 km for HANDLEY and 109 km for BOXCAR. One can see that there are significant differences between the two spectra.

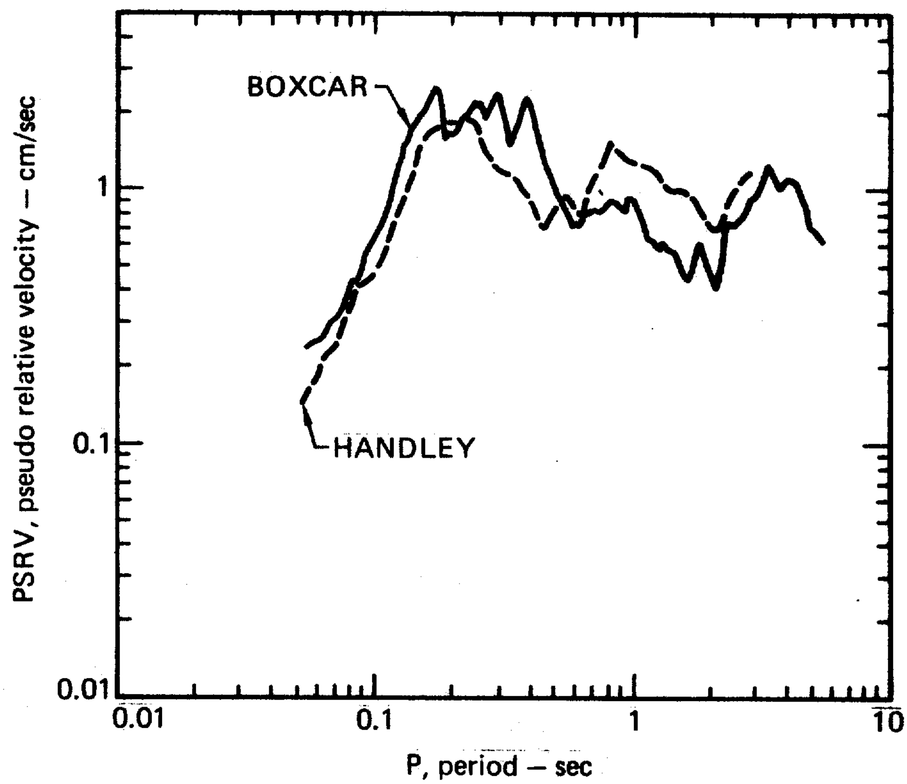


FIG. 3. Comparison of relative velocity spectra for 5% damping for BOXCAR and HANDLEY UNEs, Tonopah motel.

Figure 4 from Lynch (10) shows the reduction in the dispersion of the same data when they are analyzed by a covariance analysis that explicitly includes each site rather than a typical regression analysis. Source and travel path variations for each site were minimized by restricting the data to only UNEs located on Pahute Mesa. The level of ground motion was low so that site soil nonlinear effects should be small. Figure 4 shows that fixing the site and reducing the possible source and travel path variations significantly reduce the scatter of data about the mean. A significant variation can still be attributed to relatively minor changes in travel path and source conditions.

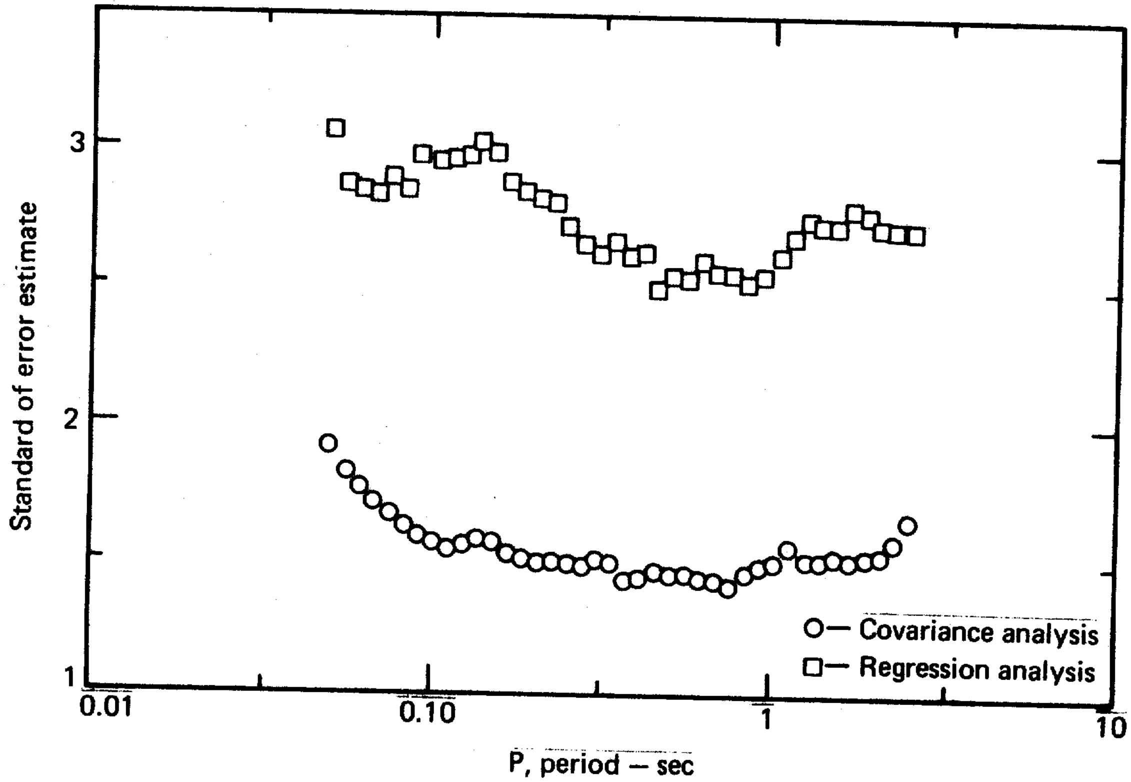


FIG. 4. Plot of standard error of estimate as a function of period for UNEs located on Pahute Mesa.

VARIATIONS DUE TO SITE FACTORS

If a given site has experienced a number of earthquakes and has records of the ground motion, then it is possible to determine if the site generally amplifies ground motion relative to typical correlations such as those developed by McGuire (11). It is also possible to determine if the data at a given site are less dispersed than the more general data set for a number of sites. The difficulty is to assess the role that site response factors play relative to source and travel path factors. As the preceeding two sections have indicated, source and travel path variations are extremely important. It is difficult to account directly for these factors other than by the simple approach of grouping the available data so that these factors are minimized.

For this study, five sites in the state of California have been chosen for which there are sufficient data to address these questions. The sites used in this study are (1) El Centro, (2) Ferndale, (3) Hollister, and two temporary sites near Oroville, California: (4) the Oroville Airport, and (5) the Johnson Ranch.

The El Centro and Ferndale sites have the most complete data set: Table 1 gives the earthquake data recorded at the El Centro site, and Table 2 gives the data for Ferndale. A number of different references were used to develop these tables, and different data sets often have significant differences among themselves; no significant effort was undertaken to reconcile the discrepancies among different data bases.

Both of these sites are deep soil sites, although the overall soil depth is greater at El Centro than at Ferndale, where the earth is somewhat stiffer than at the El Centro site. See Ref. 12 for the detailed information for both sites.

Sufficient data have been recorded at these two sites to compare the peak acceleration to the mean predicted by typical correlations among peak acceleration, site type, earthquake magnitude, and distance. For comparison, the most recent correlation developed by McGuire (11) was chosen as representative. For soil sites, McGuire determined that

$$a = \frac{24.5 \exp[0.89M]}{R^{1.17}} \; ; \sigma_{lna} = 0.62 \; , \qquad (2)$$

where

M = Local Richter magnitude

R = Distance from energy release

σ = Standard deviation

TABLE 1. Earthquake groups at El Centro.

Earthquake date	Group	Groups from Ref. 15	M_L	R, km	Peak accel. g's
4/12/38	S	I	3.0	16	0.05
12/16/55	S	I	4.3	27	0.03
12/16/55	-	I	3.9	30	0.007
12/16/55	S	I	5.5	27	0.07
10/21/42	-	II	6.5	44	0.06
4/8/68	A	II	6.4	72	0.13
1/23/51	S	II	5.6	25	0.03
1/14/53	S	II	5.5	19	0.04
12/30/34	A	III	6.5	60	0:18
6/6/38	-	III	4.0	71	0.01
5/18/40	A	III	6.5	15	0.31
9/7/66	L	III	6.3	150	0.015
2/9/56	L	IV	6.8	119	0.05
2/9/56	L	IV	6.1	119	0.015
11/12/54	L	IV	6.3	148	0.03
6/5/38	-	-	5.0	35	0.03

Group A = Large high-peak acceleration earthquakes.

Group L = Large distant earthquakes.

Group S = Small earthquakes nearer than 30 km.

- Not in the California Institute of Technology data set; only peak g values available.

M_L = Local magnitude.

R = Approximate distance to nearest center of seismic energy release.

TABLE 2. Earthquake groups at Ferndale.

Earthquake date	Group	M_L	R, km	Peak accel. g's
10/7/51	A	6.0	56	0.11
12/21/54	A	6.5	40	0.2
9/11/38	B	5.5	55	0.14
2/9/41	A	6.6	100	0.06
9/22/52	B	5.4	45	0.07
6/5/60	B	5.7	60	0.07
12/10/67	B	5.8	40	0.23
7/6/34	not used	?	131	0.01
2/6/37	not used	?	85	0.04
10/3/41	A	6.4	30	0.12
5/24/58	-	4.8	19	0.04
8/8/60	-	6.0	165	0.06
9/11/61	-	3.8	30	0.04
2/7/69	-	4.6	30	0.12
2/26/71	-	5.2	62	0.04
9/12/71	-	4.6	100	0.05
8/8/73	-	5.1	25	0.14
11/14/75	-	5.1	20	0.18
6/7/75	-	5.5	25	0.19

Group A = Large high-peak acceleration earthquakes.

Group L = Large distant earthquakes.

Group S = Small earthquakes nearer than 30 km.

- Not in the California Institute of Technology data set; only peak g values available.

M_L = Local magnitude.

R = Approximate distance to nearest center of seismic energy release.

Figure 5 shows a comparison of the recorded acceleration at the El Centro and Ferndale sites normalized by exp 0.89M as a function of R. Also shown is the mean normalized line given by Equation (2) and the $\pm$ one-sigma lines. It is evident from this figure that consistently higher-than-average peak accelerations are recorded at the Ferndale site during the earthquakes. The El Centro site appears to have average acceleration.

In order to quantify the dispersion of the data, separate regression analyses were performed for the data at the El Centro and Ferndale sites. The results of these analyses are:

$$\ln(a) = 4.82 + 0.52M - 0.83 \ln(r)$$

$$\sigma_{\ln a} = 0.39$$

for Ferndale, and

$$\ln(a) = 4.12 + 0.53M - 0.85 \ln(r)$$

$$\sigma_{\ln a} = 0.67$$

for El Centro.

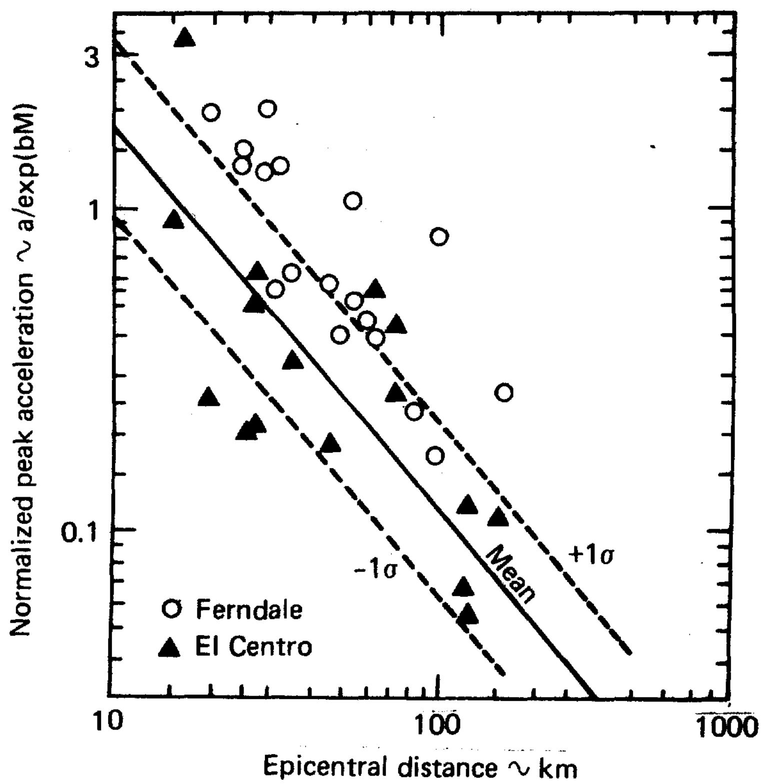


FIG. 5. Normalized peak accelerations recorded at El Centro and Ferndale sites compared with McGuire's correlation.

There is significantly less scatter to the data at the Ferndale site than to the data at the El Centro site. The data at El Centro have about the same standard deviation as the more general data set used by McGuire, which included eight El Centro records and nine Ferndale records. Although the distances R for the Ferndale events are less certain than for El Centro events, no systematic error exists (13) and it is unlikely that the errors are large enough to significantly change the conclusions reached above.

The data set for the El Centro site can be enlarged somewhat by including Trifunac's analysis (14) of the May 1940 main event and initial aftershock. If we considered just the restricted data set of the main event and the initial aftershocks at El Centro, we should have minimized differences in travel path. For this restricted data set, the regression analysis yields a much smaller value of the standard deviation of $\sigma_{\ln a} = 0.2$. As a matter of some interest, a similar analysis was performed for the main event and initial aftershocks of the San Fernando earthquake recorded at the Pacoima Dam site. For the Pacoima Dam data set, $\sigma_{\ln a} = 0.33$.

Trifunac and Udwadia (15) examined the motions recorded at the El Centro site. They grouped the earthquakes by location (see Table 1) so that the travel paths and fault systems of the groups were similar. They then compared the Fourier amplitude spectra of the acceleration for the earthquakes in each group, and concluded that different events showed little or no correlation among the spectral peaks. They reached the same conclusion when using microtremor data.

The data at the El Centro site were reexamined using the damped acceleration spectrum. The damped acceleration spectrum better defines the high-frequency part of the spectrum that is of most interest in the design of nuclear power plants. In addition to the four groups defined by Trifunac and

Udwadia, three additional groups were defined based on magnitude, epicentral distance, and peak acceleration (designated by S, A, and L) at the site. These groups are also given in Table 1.

Instead of just comparing spectra among earthquakes of the same group, average and one-sigma spectra were also developed for each group. To develop these spectra, each earthquake was scaled to one g by use of peak acceleration scaling. It was hoped that the averaging would reinforce the site periods while smoothing out the variations to the source and travel path conditions. The one-sigma spectrum would give a measure of the correlation at various site periods. If there is no correlation among records on the basis of site effects, one would then expect to see a smooth mean spectrum. The character to the spectral shape comes from correlations among events due to source, travel path, and site effects. Figure 6 is a typical comparison of three groups of earthquakes. As can be seen from Table 1, Group A contains large earthquakes with peak accelerations greater than 0.13 g at the El Centro site. Group S contains small-magnitude earthquakes, and Group L contains the large distant earthquakes. As discussed earlier (Fig. 1), it is seen from Fig. 6 that the larger magnitude earthquakes have more low-frequency content than the smaller earthquakes have, and the more distant earthquakes have more low-frequency content than the earthquakes nearer the site. It should be noted that at low frequencies the spectra are not reliable. At low frequencies, the noise-to-signal ratio is high, and the filtering of the records is suspect. Thus, reference to low frequency is in the range of 0.5 Hz to 1 Hz. It is interesting to note that the smaller magnitude earthquakes have significantly more high-frequency content than the larger magnitude earthquakes at the El Centro site.

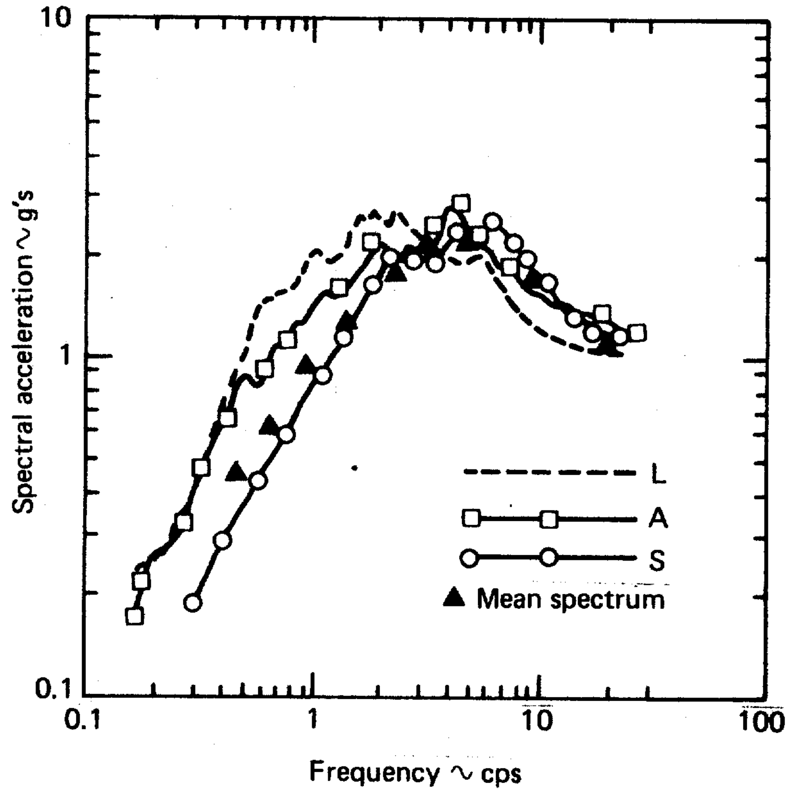


FIG. 6. Comparison of mean normalized acceleration spectra for 5% damping at El Centro for groups A, L, and S to mean of Dalal.

For comparison purposes, the mean spectrum, as computed by Dalal (16), using most of the earthquakes included in NRC Regulatory Guide 1.60, is shown by the triangle symbols. NRC Regulatory Guide 1.60 spectra are not true one-sigma spectra but rather a compromise between separate studies, along with some conservative smoothing. However, there are only negligible differences between the one-sigma spectra obtained by Dalal (16) and Regulatory Guide 1.60. Thus, Dalal's values correspond to the "mean Regulatory Guide 1.60 spectra."

Figure 7 compares the one-sigma spectra for Groups A and S to Regulatory Guide 1.60. There appears to be a site-resonant frequency at around 5 Hz that is of some importance in driving the one-sigma site response above Regulatory Guide 1.60.

By comparing Figs. 6 and 7, it is seen that at the spectral peaks there is considerable dispersion so that both the mean and one-sigma site spectral peaks are above the mean of Dalal and Regulatory Guide 1.60, respectively.

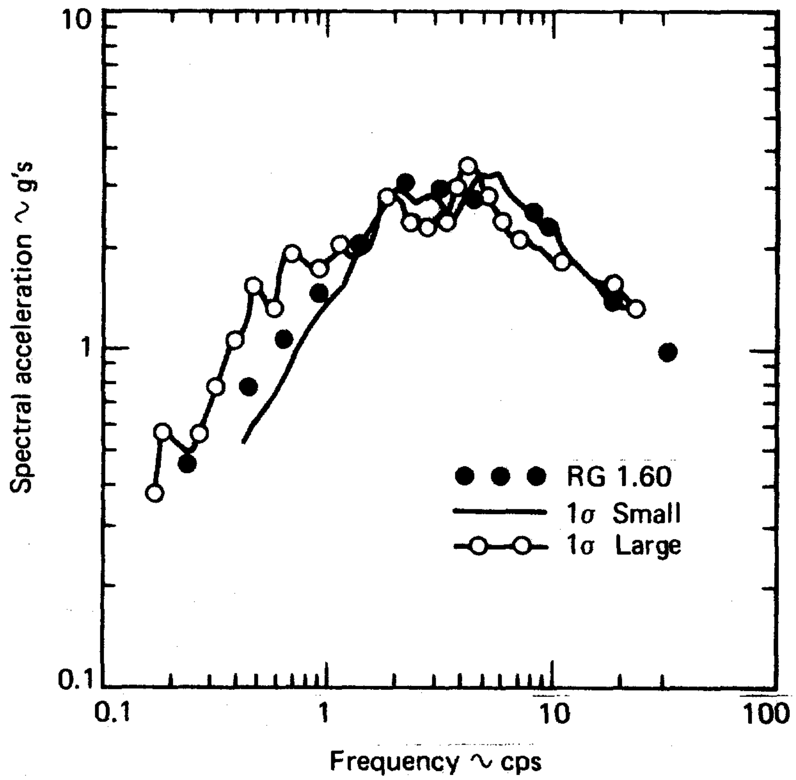


FIG. 7. Comparison of one-sigma normalized acceleration spectra at El Centro for 5% damping for groups A and S to RG 1.60.

The smaller earthquakes (Group S) were too far away to cause significant ground motion at the site. This distance effect presents two problems. First, because the ground motion is low, the nonlinear soil effects are expected to be less important, and thus it is difficult to draw comparisons between the spectral shapes obtained between, for example, Groups A and S. The second problem is that the higher frequencies are attenuated much more rapidly than the lower frequencies. Just how important this attenuation can be is illustrated in Fig. 8, which shows the spectrum (scaled to 1 g) of a small (M_L = 4.3) nearfield (R = 6.2 km) higher g value (a_{max} = 0.3 g) earthquake recorded at the Brawley Airport on January 25, 1975. This site is near the El Centro site and thus should have similar characteristics. It can be seen, however, that there is a significantly greater high-frequency content in this record than there is for the more distant earthquakes of groups recorded at El Centro. It will be seen later that this greater high-frequency content

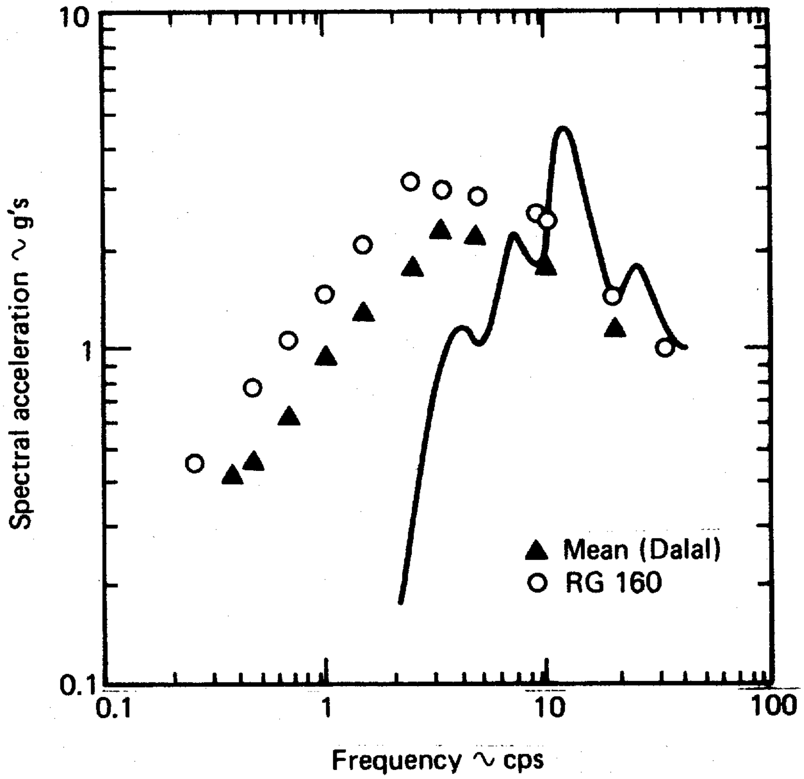


FIG. 8. Comparison of normalized acceleration spectrum for 5% damping for an earthquake at Brawley, M_L = 4.3, R = 6.2 km peak accel. = 0.3 g to RG 1.60.

is typical of small nearfield earthquakes. Hartzell and Brune (17) found that this particular event was a high-stress drop earthquake and thus the corner frequency is higher than those recorded at El Centro. The corner frequency for the smaller earthquakes (Group S) recorded at El Centro is somewhat obscured because of the probable greater generation of surface wave content due to the epicentral distances at El Centro.

There are ten strong motion recordings in the California Institute of Technology series of uniformly processed data at the Ferndale site. These were broken up into groupings given in Table 2 based on magnitude. Group A has the larger magnitude earthquakes. Figure 9 shows a comparison between the one-sigma acceleration spectra for Groups A and B and Regulatory Guide 1.60 all scaled to one g. The spectral peaks (site resonant frequencies?) are somewhat less pronounced than those for the El Centro site, although, once again, the spectral peak at around 5 Hz is significant. The smaller magnitude group (Group B) has more high-frequency content.

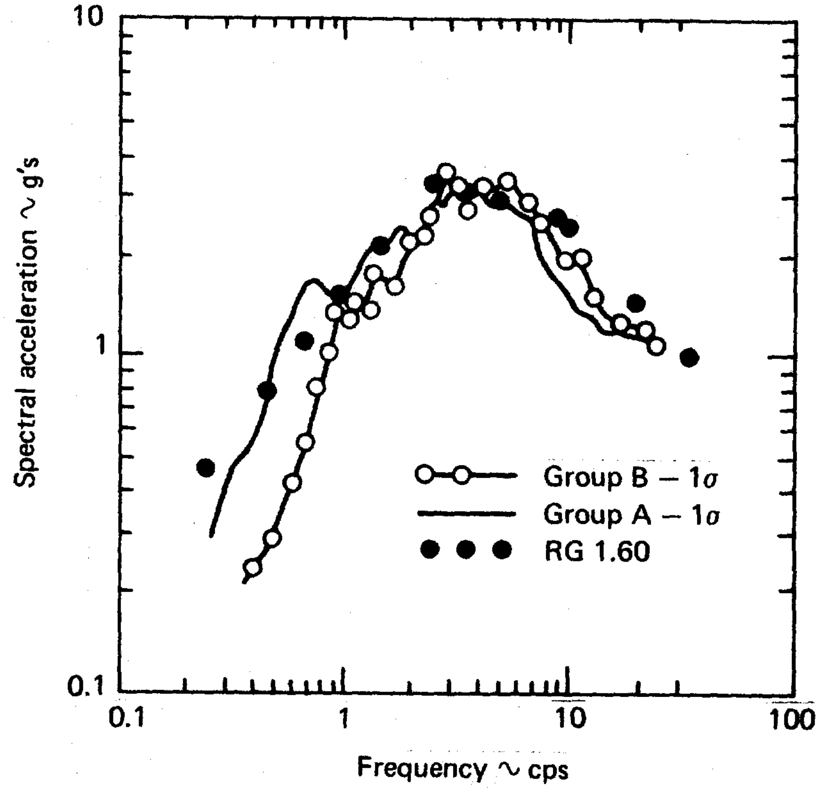


FIG. 9. Comparison of one-sigma normalized acceleration spectra at Ferndale for 5% damping for groups A and B to RG 1.60.

The Ferndale site is a one-sigma site relative to speak acceleration, but one sees in Fig. 9 that there is no significant high-frequency content in the ground motion. Examination of the time histories shows that a number of records could be characterized as having one anomalous peak much higher than the rest of the record. Thus, the spectral amplification factors are relatively low.

Table 3 shows the earthquake data recorded at City Hall, Hollister. Hollister is generally listed as a soft-soil site. The site is located very near the Calaveras fault zone and may well be in the fractured zone. Figure 10 gives the mean and one-sigma acceleration spectra for the records listed in Table 3, all scaled to one g. There appear to be three important site frequencies at about 1.5 Hz, 3 Hz, and 7 Hz. There also appears to be a suppression of the high-frequency end of the spectrum--at least relative to the El Centro site--but it is impossible to determine if this is primarily a site or source effect.

Table 3. Earthquakes at the Hollister site.

Earthquake date	M_L	R, km	Peak accel., g's
4/8/61	5.6	23	0.18
3/9/49	5.2	21	0.19
4/25/54	5.3	33	0.05
1/19/60	5.0	8	0.05
4/8/61	5.6	22	0.17

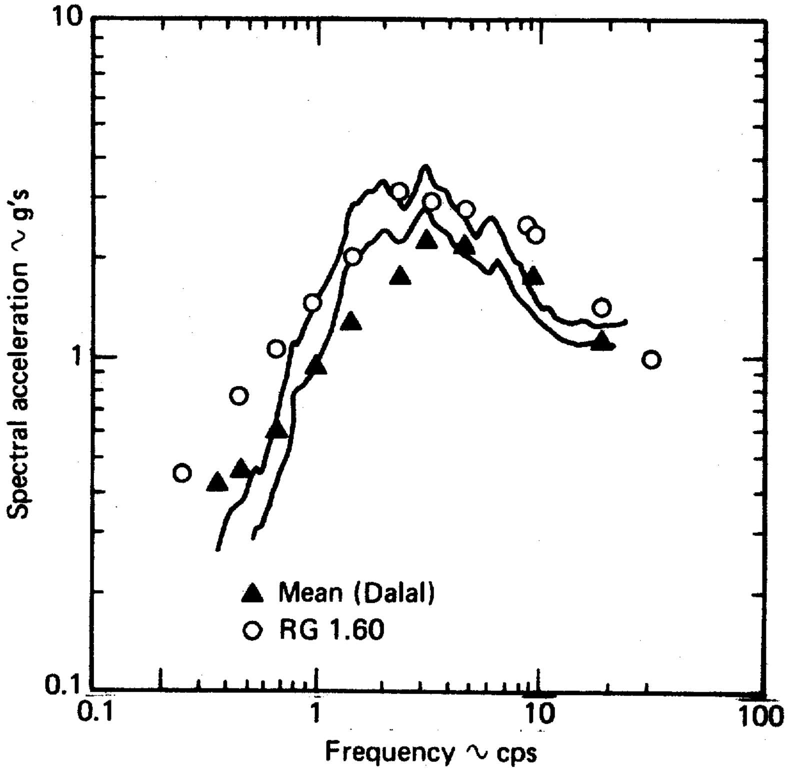


FIG. 10. Comparison of mean and one-sigma normalized acceleration spectra at Hollister for 5% damping to RG 1.60.

Table 4 shows the earthquakes recorded at the Oroville Airport and at the Johnson Ranch (18). Two groups of earthquakes were studied for each site based on peak g level. The airport is on deep soil, whereas the Johnson Ranch is on very shallow soil. The peak accelerations recorded at Johnson Ranch during the aftershock sequence of the August 1975 earthquake at Oroville were consistently high as compared with the entire data set including rock sites, suggesting a strong site-amplification effect at the Johnson Ranch (18). Figures 11 and 12 show the mean and one-sigma acceleration spectra for the airport and Johnson Ranch for the high-g value Group A for each site. The records were scaled to one-g peak acceleration.

TABLE 4. Earthquakes at Oroville Airport and Johnson Ranch.

Earthquake date	M_L	R airport, km	R ranch, km	Peak accel. airport, g's	Peak accel. ranch, g's
8/2	5.1	15	-	0.05	-
8/2	5.2	15	-	0.03	-
8/3	4.6	13	-	0.06	-
8/3	4.1	12	-	0.11[a]	-
8/6	4.7	13	13	0.25[a]	0.70[a]
8/6	3.0	-	13	-	0.11
8/6	3.6	13	13	0.05	0.16
8/8	4.9	13	13	0.08	0.21
8/11	4.3	-	6	-	0.20
8/16	4.0	-	11	-	0.22
9/26	4.0	-	13	-	0.24[a]
9/27	4.6	15	17	0.33[a]	0.58[a]

[a] High peak acceleration value records used to compute mean and one-sigma spectra for Figs. 11 and 12.

M_L = Local magnitude.

R = Hypocentral distance.

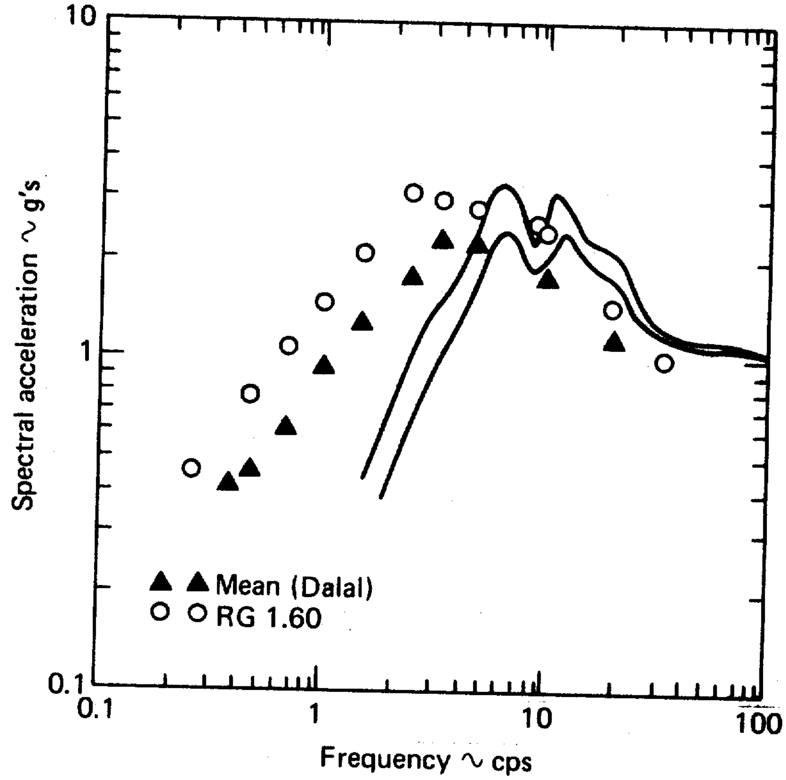


FIG. 11. Comparison of mean and one-sigma normalized acceleration spectra at Oroville Airport for 5% site damping to RG 1.60 (only higher g value records used).

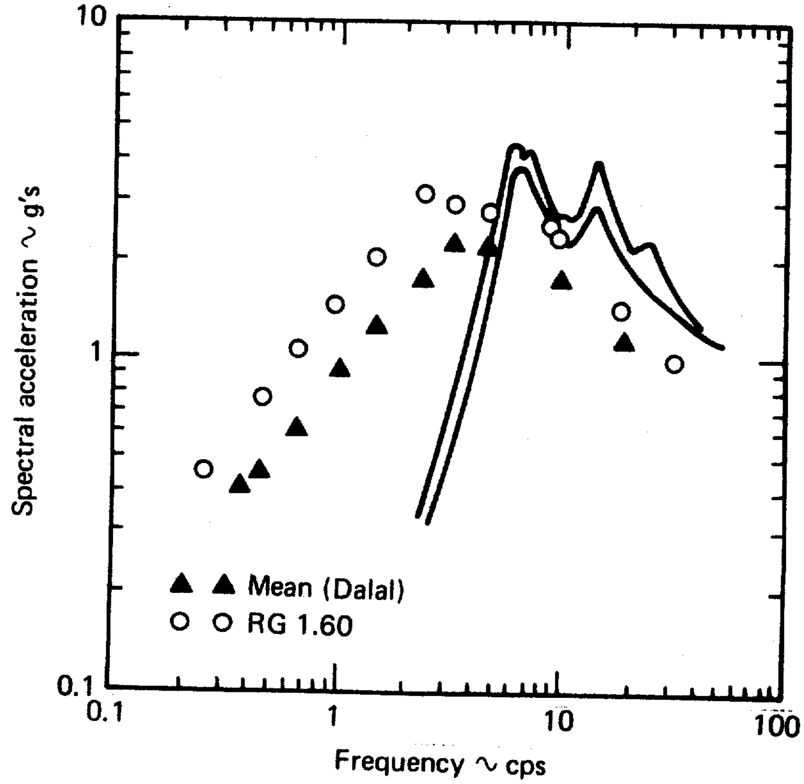


FIG. 12. Comparison of mean and one-sigma normalized acceleration spectra at Johnson Ranch for 5% damping to RG 1.60 (only higher g value records used).

The spectral amplification factors for the Oroville Airport are similar to the factors for the Brawley Airport shown in Fig. 8. The maximum spectral acceleration amplification for a 5% critical damping observed at the Oroville Airport was about 4 at approximately 11 Hz, which is about the same as the 4.5 amplification factor observed at Brawley. The Johnson Ranch data show a very strong amplification at 6 Hz with a maximum amplification factor of the 5% critically damped spectral acceleration factor of about 5. Because the Johnson Ranch site is very shallow soil, one would expect the first site-resonant frequency to be around 6 Hz. The soil at the airport is much deeper; hence, the spectral peaks observed at 6 and 11 Hz could be due to higher site modes. The fundamental site mode at the airport is not evident because the corner frequencies for the earthquake were most likely much higher than the lowest site-resonant frequency.

It is possible that the peaks are source effects or a combination of source travel path and site effects. However, average spectra based on all the records listed in Table 4 for the two sites show larger amplification factors than those shown in Figs. 11 and 12. Because a number of different earthquakes are involved, it would appear to argue for the peaks to be associated with site rather than the source effects.

Even when the earthquakes at each site were grouped to minimize various factors (e.g., magnitude, travel path, and site soil nonlinear effects), the dispersion of the spectral amplification factors about the mean as measured by the standard deviation was about the same as the dispersion found by Dalal (16). Thus, as seen in Figs. 6-10, both the mean and one-sigma spectra are above the mean and Regulatory Guide 1.60 at the site-resonant frequencies.

It is of interest to identify what site conditions make a site a one-sigma site. The problem in trying to do this is, of course, that only a few recording sites have experienced a number of strong earthquakes. An alternative approach is to look at how several sites respond to the same earthquake. Unfortunately, only the San Fernando earthquake was recorded at enough sites to make meaningful judgments.

There are a number of different ways to look at the data. In this paper, the peak acceleration was used first because it is a parameter of considerable interest, and second, because it simplifies the problems involved with the use of such parameters as spectral level at various frequencies. The least squares fit between peak acceleration and epicentral distance for the data from the San Fernando earthquake was found to be

$$\begin{aligned} \text{Ln } a &= 10 - 1.42 \ln R \\ \sigma_{\ln a} &= 0.39 \end{aligned} \tag{3}$$

It should be noted that there is considerable uncertainty as to the appropriate distance to assign each station. Epicentral distance was used for this study because Hanks (19) showed that the main energy release was around the initial focus.

At least for one interpretation of the San Fernando data set, fixing the source reduces the uncertainty as compared with the general case for which McGuire (11) found $\sigma_{\ln a} = 0.62$. This amounts to about a factor of 1.3 greater dispearsion for the general case.

In the discussion on travel path (Fig. 4), it was determined that for the UNEs located on Pahute Mesa the path variations led to a dispersion $\sigma = 1.5$ as compared with $\sigma = 1.5$ for site and travel path factors for the San Fernando earthquake. Clearly, one cannot reach a conclusion from one earthquake and results from the ground motion from UNEs; however, it is indicative of the possible importance of travel path relative to site factors.

The ± one-sigma acceleration was predicted using Eq. (3) at each site to determine which sites had recorded peak accelerations greater (or less) than the ± one-sigma level. Figure 13 from Ref. 20 shows the approximate location of the stations that are within 100 km of the epicenter.

There appears to be a directional bias between the + one-sigma and the - one-sigma sets; this bias suggests that the radiation pattern of seismic energy may be important. The regional geology is extremely complex; hence, it is very difficult to assume that site conditions are similar even though two sites may be near each other. Few sufficiently deep borings exist near recording sites to confirm the true site soil column and/or possible variations for nearby sites. Finally, it is not known how building resonance or size might affect the recorded data.

For the most part, the one-sigma stations are scattered, although this may well be due to a lack of stations. However, in the central Los Angeles area, there are a number of stations. A study of these stations illustrates the difficulties encountered in making judgments. For example, there is a group of six stations shown on Fig. 13 that are + one-sigma sites. Borings (21, 22) exist near several of these sites (Stations 137, 145, 147, 157) which indicate that shale exists very close to the surface (from 0' to 20'). Clearly, we might expect some amplification in the thin soil layer. However, Station 190, which is not too far away, also has a similar soil profile, but it is a minus one-sigma site. Figure 14 shows that there is little difference in the spectral shapes of the two sites (137 and 190), only in spectral level. The same is true for the other two components. There does not appear to be either a local site effect or a filtering effect that can be used to explain the significant differences in spectral level between these two nearby sites.

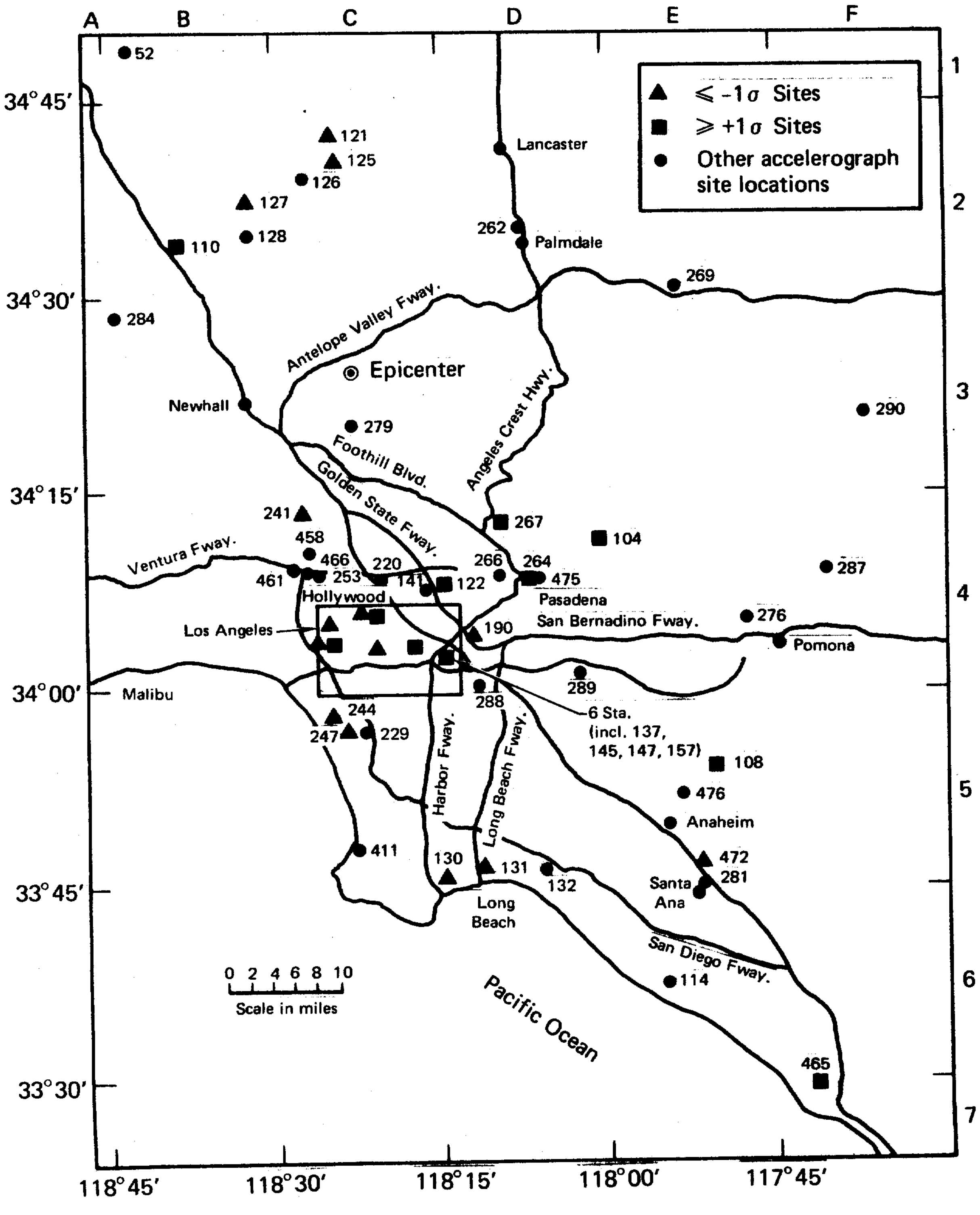


FIG. 13. Location of sites with peak horizontal acceleration $\geq + 1\sigma$ and $\leq - 1$.

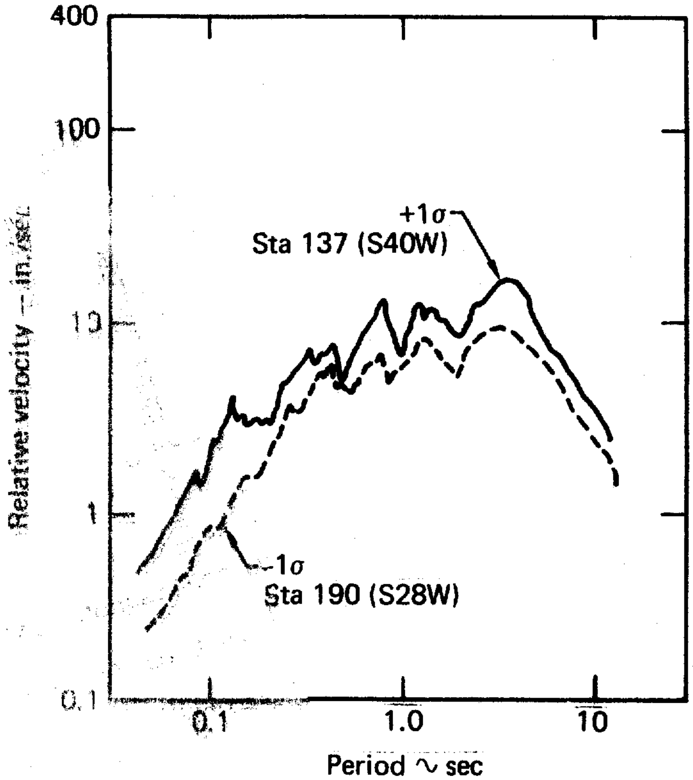


FIG. 14. Comparison of 5% damped relative velocity spectra for Sta. 137 (+ 1 σ site) to Sta. 190 (- 1 σ site). Both sites on shale 4 km apart and at an epicentral distance of 43 km.

In Fig. 15, the area around Station 199 also exemplifies the complexity of the problem. Figure 15 shows the location of several nearby sites, the ratio of recorded acceleration to the predicted one-sigma acceleration, and the depth to rock. There are very radical changes in the soil column in this area (21, 22). It is difficult to explain the variation in recorded ground motion by site, soil-structure interaction effects, or traveling wavefoundation size effects (23, 24).

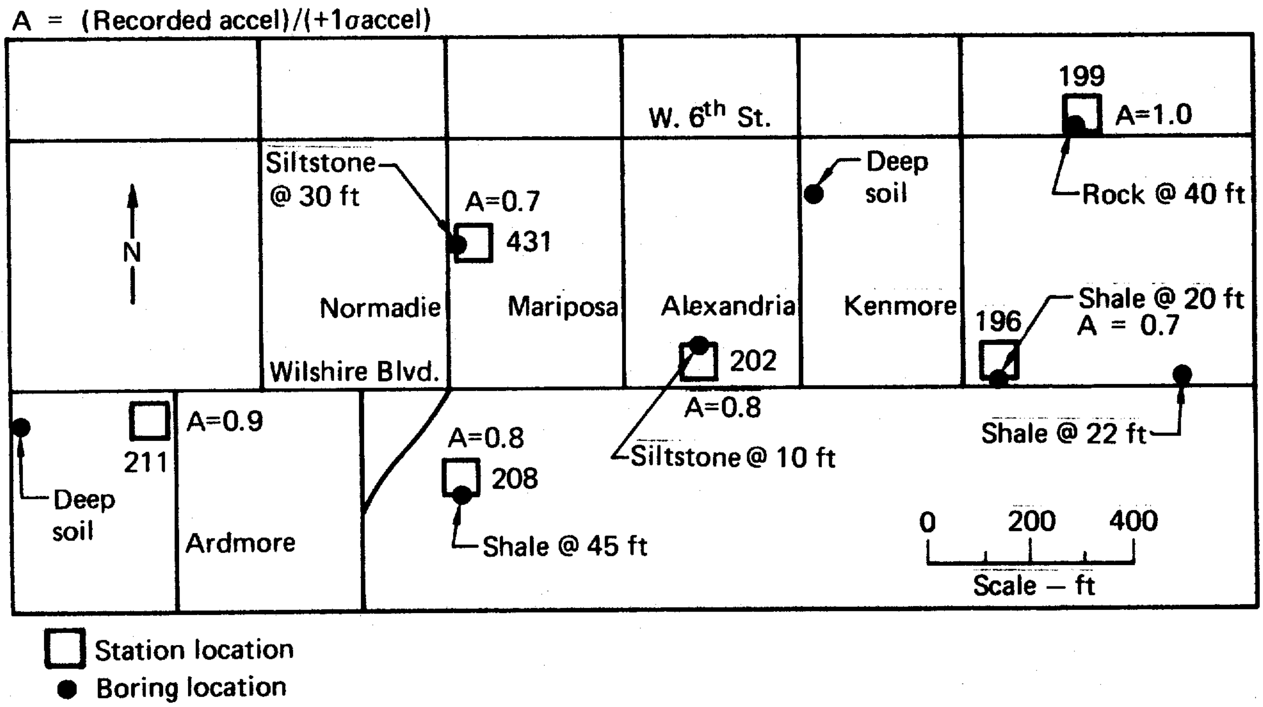


FIG. 15. Relative location of stations, depth of soil, and relative amplification of peak acceleration in the vicinity of Sta. 199.

CONCLUSIONS

The conclusions reached in this study and summarized below must be considered to be limited and provisional because so little appropriate data are available to substantiate them.

It has been shown that considerable variation in both the spectral level and the content of the ground motion can be expected between earthquakes of the same magnitude. Thus, even if travel path and local site variations are eliminated, it is still necessary to use a reasonably large value for the standard deviation to account for the dispersion of the data about the mean line of the various correlations between earthquake magnitude and ground motion parameters.

The motion observed at a site has been shown to be sensitive to minor variations in travel path. The data suggest that if the travel path is fixed relative to a given site, then the peak acceleration as a function of magnitude and epicentral distances has less dispersion about the mean relation. This reduction does not appear to carry over to spectral amplification factors in the frequency bands of most interest.

All five of the sites studied appear to have site-resonant frequencies with average and one-sigma responses somewhat above the envelope spectra obtained from averaging data from a number of different sites. Smaller near-field earthquakes have considerable high-frequency content even at relatively soft soil sites. This shape does not seem to be adequately accounted for in the approaches currently being used to develop the seismic input ground motion for nuclear power plant design.

Because of the large dispersion of the data caused by source and travel path effects, it is very difficult to determine what site types tend to respond in a "one-sigma" manner. Examination of the $\pm$ one-sigma sites from the San Fernando earthquake shows how difficult it is to make generic assessments because of possible travel path effects and the complexity of the subsurface geology.

ACKNOWLEDGMENTS

The author would like to acknowledge Drs. Brady and Perez of the U.S. Geologic Survey for making the uncorrected time histories of the Oroville earthquakes available and Dr. Hartzell for providing the time history of the Brawley earthquake. Funding from the U.S. Nuclear Regulatory Commission is also acknowledged.

REFERENCES

1. Pacific Gas and Electric Co., "Seismic Evaluation for Postulated 7.5M Hosgri Earthquake," Amendment 52, Vol. V, Units 1 and 2, Diablo Canyon Site, U.S. Nuclear Regulatory Commission. Dockets Nos. 50-275 and 50-323, 1977.
2. Smith, P., et al., Seismic Safety Margin Research Program--Program Plan, Lawrence Livermore Laboratory, Livermore, Calif., UCID-17824 (1978).
3. Trifunac, M. D., and Brady, A. G., "On the Correlation of Seismic Intensity Scales with the Peaks of Recorded Strong Ground Motion," BSSA 65, 139-162 (1975).
4. U.S. Nuclear Regulatory Commission, Standard Review Plan, NUREG-75/087, U.S. NRC, Washington, D.C. (1975).
5. Bernreuter, D. L., "A Geophysical Assessment of Near-Field Ground Motion and the Implications for the Design of Nuclear Installations," in Proc. of the Specialist Meeting on the 1976 Friuli Earthquake and the Anti-seismic Design of Nuclear Installations (Rome, Italy, October 1977), vol. II, pp. 429-459.
6. Trifunac, M. D., "Analysis of Strong Earthquake Ground Motion for Prediction of Response Spectra," Int. J. of Earthquake Engineering and Structural Dynamics 2, 56-69 (1973).
7. Thatcher, W., and Hanks, T. C., "Source Parameters of Southern California Earthquakes," J. Geophys. Res. 78, 8547-8576 (1973).
8. Bernreuter, D. L., Norris, D. M., and Tokarz, F. J., "Shock Input Earthquake Studies Using Ground Motion from Underground Nuclear Explosives," Shock and Vibration Bull., 21-31, January 1972.

9. Bernreuter, D. L., and Tokarz, F. J., "Providing an Earthquake-Like Environment for Testing of Full-Scale Structures by Using the Ground Motion from Underground Nuclear Tests," Proc. of the 5th World Conf. on Earthquake Engineering (Rome, Italy, 1973).

10. Lynch, R. D., Covariance Analysis of Response Spectra, AEC Report NVO-1163-TM-24 (May 1971).

11. McGuire, R. K., "Seismic Ground Motion Parameter Relations," J. of the Geotech Div., ASCE paper 13661, 481-490 (April 1978).

12. Shannon and Wilson, Inc., and Agbabian Associates, Geotechnical and Strong Motion Earthquake Data from U.S. Accelerograph Stations, Ferndale, Cholame and El Centro, USNRC Report NUREG-0029 (1976).

13. Smith, S., Personal Communication.

14. Trifunac, M. D., "Techtonic Stress and the Source Mechanism of the Imperial Valley Earthquake of 1940," BSSA 62, 1283-1302 (1972).

15. Trifunac, M. D., and Udwadia, F. E., "Comparison of Earthquake and Microtremor Ground Motions in El Centro, California," BSSA 63, 1429-1460 (1973).

16. Dalal, J., Probabilistic Seismic Exposure and Structural Risk Evaluation, Ph.D. thesis, Stanford University, Stanford, Calif. (1973).

17. Hartzell, S. H., and Brune, J. N., "Source Parameters for the January 1975 Brawley-Imperial Valley Earthquake Swarm," Pure and Applied Geophysics 115, 301-316 (1977).

18. Seekins, L. C., and Hanks, T. C., "Strong Motion Accelerograms of the Oroville Aftershocks and Peak Acceleration Data," BSSA 68, 677-690 (1978).

19. Hanks, T. C., "The Faulting Mechanism of the San Fernando Earthquake," J. Geophys. Res. 79, 1215-1229 (1974).

20. Maley, R. P., and Cloud, W. K., "Strong Motion Accelerograph Records," San Fernando, California, Earthquake of February 9, 1971, U.S. Dept. of Commerce, Washington, D.C. (1973).

21. Shannon and Wilson, Inc., and Agbabian Associates, Data from Selected Accelerograph Stations at Wilshire Blvd., Century City and Ventura Blvd., Los Angeles, USNRC Report NUREG/CR-0074 (1978).

22. Shannon and Wilson, Inc., and Agbabian Associates, Verification of Sub-Surface Conditions at Selected "Rock" Accelerographs Stations in California, USNRC Report NUREG/CR-0055.

23. Bernrueter, D. L., "Assessment of Seismic Wave Effects on Soil-Structure Interaction," Proc. 4th SMRIT Conf. (San Francisco, Calif., August 15-19, 1977) vol. K, paper K2/14.

24. Crouse, C. B., Engineering Studies of the San Fernando Earthquake, Earthquake Engineering Research Laboratory, California Institute of Technology, Pasadena, Calif., EERL 73-04 (1973).